

# Human Exploration Framework Team: Strategy and Status

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*Abstract*—Human Exploration Framework Team (HEFT) was formulated to create a decision framework for human space exploration that drives out the knowledge, capabilities and infrastructure NASA needs to send people to explore multiple destinations in the Solar System in an efficient, sustainable way.<sup>1 2</sup> The specific goal is to generate an initial architecture that can evolve into a long term, enterprise-wide architecture that is the basis for a robust human space flight enterprise.

This paper will discuss the initial HEFT activity which focused on starting up the cross-agency team, getting it functioning, developing a comprehensive development and analysis process and conducting multiple iterations of the process. The outcome of this process will be discussed including initial analysis of capabilities and missions for at least two decades, keeping Mars as the ultimate destination. Details are provided on strategies that span a broad technical and programmatic trade space, are analyzed against design reference missions and evaluated against a broad set of figures of merit including affordability, operational complexity, and technical and programmatic risk.

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<sup>2</sup> IEEEAC paper#1759, Version 1, Updated 2010:11:29

## 1. BACKGROUND

The Human Exploration Framework Team was chartered in April 2010 by NASA Administrator Charles Bolden for the purpose of creating a decision framework for human space exploration that drives out the knowledge, capabilities and infrastructure that NASA needs to send people to explore multiple destinations in the Solar System in an efficient, sustainable way. As its most basic function, HEFT provides strategy planning to NASA senior leadership as they plan the space flight activities for human exploration beyond Low Earth Orbit.

In order to understand the need for creating HEFT, one must understand that decision within the context of the past year. In the summer of 2009, a new strategic option emerged in contrast to the Apollo-like Constellation program. This option is best described as a “stair-step” approach toward human exploration of Mars. The *Review of U.S. Human Space Flight Plans Committee* (Augustine Committee), chartered by President Obama with the charge of “conducting an independent review of the current program of record (Constellation) and providing alternatives to that program (as opposed to making a specific recommendation) that would ensure that ‘the nation is pursuing the best trajectory for the future of human spaceflight—one that is safe, innovative, affordable and sustainable’”, defined this “stair-step” or “Flexible Path” approach as one “steadily advancing...human exploration of space beyond Earth orbit...successively distant or challenging destinations...with no immediate plan for surface exploration...”.

The Flexible Path approach recognizes that the human-accessible solar system is richer than just the Moon and Mars. High Earth Orbit (HEO), Geosynchronous Orbit (GEO), lunar orbit, Cis-lunar space, near-Earth asteroids, Lagrange points, Mars orbit, and the moons of Mars all have

great potential for discovery and exploration by humans. In addition, the Flexible Path provides a means for dividing the epic challenge of sustaining human exploration on the surface of the Moon or Mars into increments of manageable challenges building on ever-more advanced capabilities. Figure 1 shows a mapping of possible destinations and capabilities. This means that NASA's goal would be defined as getting to a certain destination, but instead developing "the capacity for people to work and learn and operate and live safely beyond the Earth for extended periods of time, ultimately in ways that are more sustainable and even indefinite."

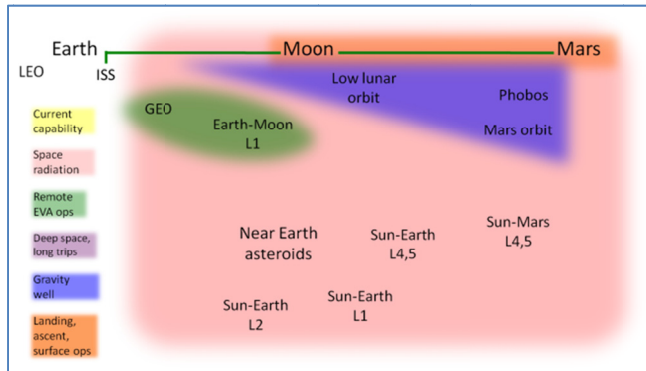


Figure 1: Flexible Path Destinations - Various program pathways through these destinations can build our capabilities

In April 2010, President Obama laid out an ambitious challenge for NASA's human space flight (HSF) program with the following main points:

- Early in the next decade, a set of crewed flights will test and prove the systems required for exploration beyond LEO.
- Finalize a rocket design no later than 2015 and then begin to build it...at least two years earlier than previously planned – and that's conservative...
- And by 2025...new spacecraft designed for long journeys to allow us to begin the first-ever crewed missions beyond the Moon into deep space...start by sending astronauts to an asteroid.
- By the mid-2030s...send humans to orbit Mars.
- And a landing on Mars will follow.

Naturally, as is expected by the policy formulation process, the executive and legislative branches spent much of 2010 in negotiation as to the final outcome; with the authorization just signed into law on Oct. 11, 2010 and the appropriations law yet to be passed. Therefore, at the time of this paper's submission, the exact nature of NASA's new direction remains undefined.

It is widely apparent that NASA's HSF program will undergo a major shift in direction. As early as February 2010, NASA established planning teams to assess the impact of the new direction and to remain poised to implement whatever policy decision is ultimately made.

These planning teams, each focused on a specific area of the Administration's proposed Exploration budget, needed overarching guidance in order to present an integrated human space flight plan.

This overarching guidance, or *architecture*, is critical to the success of the program and is not easily achieved. A great deal of analysis is required to understand how best to structure NASA's HSF efforts over the next 20 – 30 years. This is especially difficult as HSF programs are complex, expensive, and take decadal timescales, yet funding is annual and political cycles occur on 2, 4, and 6-year intervals. This, coupled with the fact that resources are incredibly limited (NASA is funded at less than half a percent of the federal budget) while the interests of our stakeholders are very diverse, make it almost as challenging to create a sustainable, affordable, and feasible architecture as it was to land on the moon. The 24 blue-ribbon panels that have (re)assessed HSF strategy since 1969 are evidence of this challenge.

It is to address this challenge that the Agency Human Exploration Framework Team was created. All of HEFT's products are designed to provide *decision support*; to inform NASA senior leadership by providing credible, consistent, coherent, and transparent analyses on all architecture aspects including destinations, operations, elements, performance, technologies, safety, risk, schedule, cost, partnerships, and stakeholder priorities. In other words, by way of objective analyses, inclusive trade studies, and integrated conditional choices, HEFT prepares *architecture decision packages* for NASA senior leadership. These draft multi-destination architectures are not "point solution" architectures, decision recommendations, nor specific decisions.

## 2. PHASE I APRIL - SEPTEMBER 2010

During the initial phase of HEFT, the team made a great deal of progress in establishing and exercising a consistent method for asking questions, comparing architecture alternatives, and integrating findings. HEFT examined a broad trade space of program strategies and technical approaches in an effort to meet priorities from the White House, Congress, and other stakeholders.

These priorities included but were not limited to:

- Explore Mars surface as the horizon destination for human exploration
- Conduct a routine cadence of missions
- Develop evolutionary family of systems
- Inspire through numerous firsts
- Combine use of human and robotic systems
- Exploit synergies between SMD and HSF objectives
- Fit within projected NASA HSF budget
- Include reliance on non-NASA capabilities (e.g., launches, systems, facilities)

- Minimize NASA-unique supply chain and new facility starts
- Pursue lean development and operations practices
- Use ISS
- Balance high-payoff technology infusion with mission architectures and timelines

As a starting point, the team designed a method to explore “the corners of the box” to frame the broad trade space of human exploration options. The team set up a 3x3 matrix, with strategy investment alternatives on one axis and technical approach alternatives on the other (Figure 2).

	DRM 1	DRM 2	DRM 3
Strategy 1			
Strategy 2			
Strategy 3			

The three strategic investment alternatives emphasized different aspects of the executive branch direction:

1. Technology development as a priority,
2. Early beyond LEO as a priority, or
3. NEO arrival by 2025 as a priority.

The three technical approach alternatives would implement human exploration missions using different core capabilities:

1. Reusability and advanced systems,
2. Emphasis on commercial development and refueling, or
3. Emphasis on heavy-lift.

All nine of these scenarios, or design reference missions (DRM's) were subjected to a consistent analysis process.

HEFT also began two other assessments in order to more fully understand the factors that would impact an architecture selection. The first of these was an assessment of technology investment priorities. NASA is actively preparing to make investments in several areas including HSF-related technologies, exploration demonstration programs, and exploration robotic precursors. Efficient use of limited resources requires aligning these plans with priorities specified by the HSF architecture NASA ultimately implements. Therefore, it was important that the

HEFT team assess the relationship between the technology investment plans and the nine potential DRM's.

The other assessment undertaken by HEFT was a stakeholder analysis. This was a difficult task as many stakeholder priorities are neither easily measured nor reconciled. However, measuring and making visible the implications of various options according to stakeholder priorities is fundamental to achieving a workable consensus so NASA can move forward.

### 3. PHASE I FINDINGS

As each of the scenarios was methodically assessed against cost, schedule, technology investment priorities and stakeholder analysis, the first-pass analysis yielded many important insights. To begin, none of the scenarios yielded an acceptable outcome; none “closed” with regard to either cost or schedule. It had become clear that there were no magic bullets and that new approaches would be needed, including “lean” system development approaches.

HEFT quickly recognized that NASA's HSF annual cost profile is the “great leveler” and constitutes the highest-priority challenge for a viable HSF architecture. It is a powerful force to drive consensus. This is important, as no affordable program plan will satisfy all major stakeholders and compromise is essential to move forward with a sustainable HSF exploration program.

Another major finding by the team is that understanding the impacts of a series of exploration missions and the potential value of system reusability requires a longer view than a 15-year analysis horizon. The development and operation of exploration-class heavy-lift and exploration-crew launch systems are major “cost wedges” that dominate program content and the cost profile for years.

Regardless of the cost wedge, the team recognized that heavy-lift launch capability is a fundamental need for human exploration beyond LEO. All but the nearest deep-space mission need it, as do planet-surface class missions.

Key investments in technology were found to be applicable to multiple destinations that NASA desires to explore. These technologies were driven out by the “technology investment” strategy mentioned above. For example, HEFT analysis was able to determine that any delay in starting mission flight system development past 2012 would likely preclude a human-to-asteroid mission by 2025.

HEFT also determined that the “NEO 2025” priority and the “Early beyond LEO as soon as possible” priority investment strategies are essentially the same. It would take several years to develop the flight systems needed for either and pre-asteroid flight tests must reach beyond LEO anyway.

The choices that NASA leaders and stakeholders face now are difficult. Fundamentally, they are about which

architecture to select and what systems to begin designing and building. These choices will define NASA's core philosophy and character for decades to come.

However, some major choices and elements can be delayed or re-phased. For example, there is time to determine which type of Mars-class in-space propulsion NASA should use. Also, a decision about whether lunar surface operations should precede Mars is not immediate. The flexible path strategy preserves options for future stakeholders. Not all decisions need to be made now, and choices that do not affect the next decade of HSF would be distracting at this point.

The greatest challenge in this process is solving the budget dilemma. Doing this will force NASA to confront fundamental challenges about the future of human exploration. A few of these challenges are:

1. **Flight Rate:** In this budget-limited reality, and without more affordable approaches, human exploration flight rates would be low – just a few through the 2020s. This conflicts with expectations conditioned by the International Space Station era.
2. **Destinations far in the future:** Any humans-to-Mars-surface mission is far in the future (2030's) even if the budget were unconstrained. Cis-lunar missions will be feasible sooner. This raises the question of how long could multiple missions to GEO or EM-L1 satisfy our beyond-LEO aspirations. Finally, the real challenge of sustaining public commitment based on a "horizon destination" so far into the future would be unprecedented in modern society.
3. **Workforce Strategy:** Sustaining the existing NASA-contractor workforce may be at odds with "lean development." At the same time, deferring the development of heavy-lift launch or the crew capsule would force NASA to "start over" (new people, new contractors, new learning) sometime in the future. We know we must accomplish more with the same workforce. NASA must ask what balance between evolutionary and revolutionary approaches is optimal. Also, how acceptable or advisable would a "start over" be?
4. **Interdependence:** While NASA has long valued its HSF partners, it has been a practice to keep "critical path" capabilities under agency control. The budget does not allow for this type of practice given the number of elements needed for beyond-LEO exploration. As it becomes more apparent that partnerships are essential, there will be more discussion around which elements can/should be developed and operated in partnership with other U.S. government agencies, the commercial sector, and the international community.

## 4. SEEKING DEEPER INSIGHT

*JULY–AUGUST 2010*

The early insights from Phase 1 were a "wake-up call" to the team, but more detailed trades and analyses were needed to understand the challenges.

For launch vehicle options, the team needed to look at implications for readiness date, cost risk, alignment with national propulsion objectives, potential development partnerships and use of existing NASA expertise. A key trade necessary to determine heavy lift options had to be between affordable DDT&E vs. affordable annual cost. A specific input into this trade analysis was the cost uncertainty, complexity, and launch rate for commercial launches.

Further analysis required for crew vehicle options included system alternatives for the ascent/descent capsule and the destination-operations vehicle. The team also needed to take a closer look at exploration implications for Orion derivatives and commercial crew vehicles. Finally, the development pace of radiation effects understanding and possible mitigations, reliable and efficient long duration ECLSS, and deep-space habitat systems are all major factors in selecting crew-carrying vehicles, and thus need in-depth study.

With regard to the trip time associated with electric propulsion, HEFT explored the implications of the size and performance of SEP systems vs. time to first asteroid mission, and the implications of long-duration operation through van Allen radiation belts.

And in order to produce a more confident cost profile, HEFT completed accounting of all elements and reconciliation of assumptions. We developed a conservative projection of available budget and allowed for near-term budget liens that create a near-term "budget keyhole".

Seeking affordability for the "NEO 2025" strategy, HEFT began optimizing the DRMs including looking at early NEO opportunities. Second-pass analysis revealed we will likely need to develop heavy-lift launch in the near term. Asteroid missions appear to stretch commercial launch capacity in ways that require more precise trades to validate:

- Advanced electric propulsion (DRM 1) halves the in-space propellant needed but nonetheless requires a large number of commercial or partner launches
- Episodic bursts of high flight rate affect the launch business case, pricing, workforce, and reliability
- NASA might end up bearing the carrying cost of an expanded commercial launch infrastructure.

In response to a number of challenging factors, HEFT created a DRM 4 option by combining DRMs 1 and 2. Some characteristics of this option were:

- 300 kWe solar electric propulsion and low-boiloff cryogenic boost stages, used in a hybrid architecture.
- 100t HLV, either human-rated or with commercial crew launch
- All expendable to start, evolving to reusability if multiple asteroid missions occur.

In addition, DRM 4 would limit the number of developments to five major flight systems, it would reach asteroids with deep-space staging, and would manifest well on a reasonable number of hardware/propellant launches with adequate margins. The DRM 4 flight elements could support both earlier and later flexible-path mission types. Unfortunately, the DRM 4 option did not “close” either.

## 5. PHASE II

*SEPTEMBER – DECEMBER 2010*

The current phase of HEFT technical work rests on the extensive foundation established by HEFT in the summer of 2010. HEFT is leveraging its “analysis engine” to conduct and validate key trades and prepare decision packages for Agency leadership to support the ongoing annual budget process with Congress and the White House.

We are working with and updating the earlier HEFT work and adding new degrees of freedom to meeting our affordability objective including:

- Elements: additional HLV options, crew vehicles, in-space systems, ground-based elements
- In-space operations: Cis-lunar staging; Cis-lunar, trans-lunar, and asteroid targets
- Partners: critical-path partnerships with other domestic and international agencies, balanced reliance on commercial launches of propellant, in-space elements, and exploration crew
- Sensitivity analyses to understand impact of varying key assumptions.

We are developing multiple architecture alternatives that may “work,” based on coherent, implementable assumptions and concepts of operation. We look for options with the potential to fit the budget and meet stakeholder objectives on acceptable schedules. We then exercise our process to refine concepts of operations that address the spectrum of operations, including destination operations, aborts, and contingencies.

This current phase of engagement will support near-term agency and stakeholder decisions. We are beginning two-way communication of ideas and concerns including partners, industrial collaborators, and the public. We have increased broadband interaction with the HEFT Steering Council to provide them effective decision support and to stay close to their evolving decision-making priorities

One of the primary products is to prepare and present decision packages to NASA senior leadership that expose and explain options and implications of various strategies and implementations. These decision packages are an integration of quantified trade and sensitivity findings with figures of merit that reflect the wide range of stakeholder needs and desires. They frame conditional choices about implementation strategies and content. The decision packages are instantiations of the elements of the initial architecture including concept of operations, that are intended to meet cost, schedule, risk, and performance expectations while leaving open design specific options and provide a basis for discussions with potential International partners.

Making it affordable is the “price of admission.” It is the primary gate through which all options must pass. Fitting an enterprise plan within projected affordability limits is “first among equals” of the many stakeholder concerns. HEFT analysis has already illuminated key boundaries, high-leverage questions to answer, and promising areas for further focus. NASA has several approaches to enhance affordability, including:

- Implementing leaner development and operation of its large-scale and human-rated systems
- Integrated phasing of element development schedules
- Partnering with other domestic and international agencies for system development and operations.

However, lean development of large HSF systems will most likely require fundamental transformation of the HSF communities (NASA and industry) ways of doing business. HEFT analysis indicates it will be enabling for human exploration (or disabling if not achieved) and will therefore define the next generation of NASA HSF.

## 6. CONCLUSIONS

The value of the HEFT activity has been proven and is widely accepted with NASA. But its job will not be done as this phase completes in December, 2010. There is a clear need for an on-going HSF architecture activity and it is expected that a HEFT-like team will continue indefinitely since the complexity and challenges of the HSF technical, programmatic and political environment will continue to evolve.

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## BIOGRAPHY



**Brian Muirhead** has worked on numerous spacecraft and technology projects, including Galileo, SIR-C, and MSTI-1, since coming to NASA's Jet Propulsion Laboratory in 1978. He was responsible for the design, development, test, and launch of the Mars Pathfinder spacecraft that landed successfully on Mars on July 4, 1997. Following this successful landing he was named Project Manager. He served as Project Manager of the Deep Impact Project from November 1999 to November 2002. In November 2002, he became the Chief Engineer of the Mars Science Laboratory mission and in August 2004 he became Chief Engineer of JPL. In February, 2007 Brian was named Program Systems Engineer for the Constellation Program, which includes responsibility for the Lunar Architecture.

He received his BS in Mechanical Engineering from the University of New Mexico in 1977 and an MS in Aeronautical Engineering from Caltech in 1982. He is the recipient of NASA's Exceptional Achievement Medal for his work on SIR-C and the Exceptional Leadership Medal for his work on Mars Pathfinder.



**Brent Sherwood** manages Strategic Planning and Project Formulation at the NASA Jet Propulsion Laboratory. This institutional function coordinates how JPL conceives, engineers, captures, and plans new opportunities for space science missions, instruments, and investigations.

Throughout 2010 Sherwood was assigned to the NASA Human Exploration Framework Team (HEFT), supporting the integration of plans for the future of human space exploration.

*Sherwood is a space architect with 22 years in civil and commercial space: the last five at JPL after 17 at Boeing. At Boeing, he led teams in concept engineering for human and robotic planetary missions, manufacturing engineering for ISS pressurized modules, program development for Sea Launch, and business development for several commercial space and space science projects.*

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